

## **Appendix B**

### **Remedial Technologies and Process Options Identification and Screening**



## Appendix B

### B.1 REMEDIAL TECHNOLOGIES AND PROCESS OPTIONS IDENTIFICATION AND SCREENING

Table B-1. Remedial technologies and process options identification and screening.

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
<b>No Action</b>						
None	None	This option entails no active remedial activities beyond existing site access controls and/or environmental monitoring currently conducted at the INEEL as part of site-wide activities.	This option is not effective at reducing COCs and/or risk to human health and the environment.	This option is implementable.	Implementation costs are expected to be low in relation to other solutions.	Retained as baseline comparison.
<b>Institutional Control</b>						
Land-use restrictions	Zoning, local permits and ordinances, use restrictions, easements, covenants, deed notices, public advisories	Land-use restrictions comprise local, state, and federal controls to restrict future land use and exposure to site contaminants (see main text for descriptions). Potential restrictions include controls on future use of area groundwater.	Land-use restrictions may control exposure pathways that could result in an unacceptable risk to human health. This option does not address ecological exposures. Deed notices and public advisories may discourage inappropriate use, but are not legally binding.	This option is implementable.	Costs are expected to be moderate to low in relation to engineered solutions.	Retained.
Access controls	Fencing	Fencing involves enclosing individual or contiguous areas within a physical barrier, such as a chain-link fence with a locking gate. This institutional control reduces risks to human health by inhibiting direct exposure to wastes and contaminated soil. Access restrictions could reduce environmental risk by limiting exposure to some animals.	Long-term effectiveness depends on enforcement and maintenance. This option could address some ecological exposures.	This option is administratively and technically implementable.	The fencing option has low capital and O&M costs, in relation to other action-specific remediation approaches.	Retained.
Environmental monitoring	Signage	Signage typically is placed at the site to inform potential intruders of site dangers and indicate restricted access.	The signage option is marginally effective as a single option. It is best combined with fencing and other access use modification. However, it does not address ecological risk.	This option is administratively and technically implementable.	The signage option has low capital and O&M costs in relation to other action-specific approaches.	Retained.
	Groundwater, air/dust, soil, biota, surface water, and moisture	This option consists of periodic media monitoring to evaluate future environmental conditions and effectiveness of implemented remedial actions (see main text for descriptions).	The effectiveness of the environmental monitoring option is not applicable.	This option is administratively and technically implementable.	The relative costs of this option are low to moderate.	Retained.
<b>Containment</b>						
Surface controls/diversions	Site grading	Site grading would recontour the surface of the SDA—or individual disposal pits, trenches, and vaults—to route water away from the waste zones and reduce infiltration. Site grading could include creation of drainage swales and/or surface water control berms. Drainage swales would facilitate transport of surface water away from the waste areas. Berms could be used around the perimeter of the SDA to prevent surface water run-on from adjacent areas.	Surface controls/diversions are effective at minimizing infiltration, but are susceptible to erosion as a stand-alone option.	This option is easily implementable.	Capital and O&M costs vary depending on project scope, but are expected to be low in relation to other surface treatments.	Retained.

Table B-1. (continued).

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
	<b>Erosion control/vegetation</b>	Erosion-control measures include physical covers—such as rock, concrete facing, or asphalt—to provide protection against impacts due to precipitation, wind, and surface water movement. Vegetation may provide this type of erosion control as well as physical cover. Vegetation provides transpiration, which removes water from the surface to a relatively shallow depth and reduces surface water infiltration. This type of surface treatment can be self-sustaining and long lasting within a given climatic zone.	This option is effective at extending the life of the capping process option. All erosion-control measures will require periodic maintenance to ensure protectiveness.	This option is implementable and is a common technology. Vegetative covers may be difficult to sustain due to climatic conditions.	Capital costs vary depending on the type of process option, but are expected to be low in relation to other surface treatments. The O&M costs are expected to be moderate.	<b>Retained.</b>
<b>Surface barriers</b>	<b>Engineered single-layer cover</b>	<p>Single-layer covers would consist of a designed thickness of a single type of material, which could include compacted soil, asphalt, concrete, or geomembrane. Covers could be used to isolate the SDA source term and provide either short-term or long-term protectiveness. The following items are different types of single-layer covers:</p> <ul style="list-style-type: none"> <li>• Soil layers could use either natural clay or a bentonite-soil blend. Clay properties such as plasticity index and particle size gradation would be specified to achieve permeability requirements. Soils would be compacted, as required, to provide consistency and achieve performance requirements. Granular soils (i.e., sands and gravels) could also be used to provide a physical barrier.</li> <li>• Asphalt is a common cover used to control and minimize surface water infiltration.</li> <li>• Concrete also could be considered as a surface barrier to prevent direct access to waste. The slab would need to be designed to withstand potential settlement that could result in cracking. A gravel layer likely would be used underneath the concrete for stress distribution. In addition, reinforcements could be installed to minimize cracking over the design life.</li> <li>• Geomembranes include the number of commercially available synthetic materials that could be used to prevent surface water infiltration. The effective life of geosynthetics exposed to weather generally does not exceed 20 years.</li> </ul>	This process option is considered to be marginally effective in achieving the project RAOs. The soil cover would be susceptible to biointrusion and desiccation cracking, which will affect long-term effectiveness. Though asphalt is a flexible cover that can be designed to control surface water infiltration, environmental forces will degrade its integrity over time, and the cover would require periodic replacement. A concrete cover would prevent direct intrusion into the waste, but its rigid nature and potential for cracking hinders its ability to achieve RAOs; as such, a concrete cover is not considered an effective long-term protective barrier. Geomembranes also have limited effective lives when exposed to the environment and will require periodic replacement.	This option is implementable. The engineered single-layer cover is a common, well-known process option that uses readily available materials.	Capital costs are expected to be low to moderate in relation to other surface capping options. The O&M costs are expected to be high, requiring complete, periodic replacements.	<p>This option has not been retained as a stand-alone process option for long-term protectiveness due to its inability to maintain integrity for the performance period required at the SDA.</p> <p>Individual design elements (i.e., soil, asphalt, concrete, and geomembranes) have been retained as individual design elements for assembly into the multilayer cover process option.</p> <p>Process option has been retained for application as a short-term protective measure during implementation of remedial activities at the site.</p>
	<b>Engineered multilayer cover</b>	<p>A number of multilayer cover designs could be potentially implementable at the site. The covers have been established to provide long-term protectiveness of contaminated sites and are designed to prevent biotic intrusion and control surface water infiltration. Potential designs include:</p> <ul style="list-style-type: none"> <li>• Standard RCRA Subtitle C cap</li> <li>• Modified RCRA Subtitle C cap</li> <li>• Long-term composite cover</li> <li>• ICDF cover.</li> </ul> <p>Specific design elements for the cover systems are presented in the main text.</p>	This option is effective at minimizing infiltration and providing a barrier between contaminants and humans and burrowing animals. Design life varies between 30 (standard Subtitle C barrier) to 1,000 years (long-term composite cover and the ICDF cover).	This option is implementable. The engineered multilayer cover is a common, well-known process option using available materials. Borrow source evaluation will be required during design to verify availability of onsite sources for soil and rock.	Capital costs are expected to be moderate in relation to other surface capping options. The O&M costs are expected to be moderate.	<b>Retained.</b>

Table B-1. (continued).

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
	<b>Biotic barriers</b>	A biotic barrier generally consists of one or more layers of coarse gravel and/or cobbles compacted to maximum density, which is intended to impede burrowing animals and human penetration. A number of potential biotic barrier designs are available, but the SL-1 cap was selected as the representative process option for this FS. The SL-1 cap, designed for INEEL's WAG 5 Power Burst Facility, consists of layers of basalt cobbles underlain and overlain by gravel, with a rock armor surface. This cap, with a total 1.8 m (6 ft) minimum thickness, was designed to control surface exposures to radionuclides and to inhibit biotic intrusion for approximately 400 years (DOE-ID/EM 1997).	This option is effective at providing a barrier between contaminants and humans and burrowing animals, but is not effective at minimizing surface water infiltration.	This option is implementable. The biotic barriers option is a common, well-known process option that uses available materials. Borrow source evaluation will be required during design to verify availability of onsite sources for rock.	Capital costs are expected to be low to moderate in relation to other surface capping options. The O&M costs are expected to be low in relation to other surface capping options.	Retained.
<b>Lateral barriers</b>	<b>Slurry wall</b>	A slurry wall consists of a backhoe or excavator-constructed trench held open with a colloidal clay and water slurry, then backfilled with a low-permeability material. Various types of backfill include soil-clay mixtures and soil-cement mixtures. The primary construction technique is the continuous-trenching method. This process option can be combined with other types of lateral barriers. Slurry walls are generally 1 m (3 ft) thick with attainable depths of over 30.5 m (100 ft).	Slurry wall is a proven technology, which will be effective in providing a barrier to the subsurface conditions within the SDA. In situ permeability and continuity are not easily monitored; so downgradient-monitoring wells should be used. Permeability for the continuous trenching technique can reach $10^{-6}$ to $10^{-7}$ cm/s.	This option is implementable. The slurry wall option is a common, well known process option, which uses standard earthwork equipment and commercially available and onsite materials. Excavation equipment can be sized to provide penetration in soils and basalt, as required to achieve design-required depths.	Capital costs are expected to be low to moderate in relation to other lateral barriers.	Retained.
	<b>Grout curtain</b>	Jet and permeability grouting techniques are used to inject grout at high pressures into the sides of a borehole to create columns of modified soil that overlap to form a low-permeability wall. Installation employs a grout tube drilled to depth in the soil to form a column by grouting from the bottom up with an ultrafine Portland cement. Multiple layers of columns form the wall. This process option for groundwater cutoff has been used for decades in dam construction and has been used with success at some sites, but is relatively new for environmental contamination applications (CH2M HILL 1996).  Grout curtains may be 1 m or more, depending on the number of layers of columns used to create the barrier. Depths over 23 m (75 ft) are attainable.	Grout curtain is a proven technology, which is effective at minimizing migration of groundwater across the barrier and, if properly designed, could be effective in the subsurface conditions within the SDA. Permeability (depending on the grout type and construction technique) ranges from $10^{-5}$ to $10^{-7}$ cm/s. Monitoring convergence of the columns at depth is difficult. Lack of continuity in the grout curtain could substantially reduce the effective permeability.	Grout curtain is a proven technology and can be installed with conventional equipment and commercially available materials. Jet grouting can be used effectively in soil types ranging from gravel to heavy clays (Mutch, Ash, and Caputi 1997) and has been repeatedly demonstrated on soil and waste sites.	Capital costs are expected to be moderate to high in relation to other lateral barriers. If properly designed, the grouted matrix would be stable in the SDA environment and, as such, the O&M costs are projected to be minor.	Retained.
	<b>In-place soil mixing</b>	Multiaxis augers and mixing paddles are used to construct overlapped columns that form a continuous wall of mixed soil and cement, bentonite, or other admixture. This process, which was developed in Japan, has been used in the U.S. for several years. The barrier is generally 0.5 to 1 m thick and can attain depths of over 30.5 m (100 ft), depending on soil conditions.	In-place soil mixing is effective at minimizing migration of groundwater across the barrier. Permeability (depending on the amount of gravel in the mixed geologic material) ranges from $10^{-5}$ to $10^{-7}$ cm/s.	The in-place soil mixing option is implementable. Multiple auger systems penetrate most geologic conditions and would be implementable in soil and basalt layers underlying the SDA.	Capital costs are expected to be moderate to high in relation to other lateral barriers. Relative O&M costs are expected to be minor.	Retained.

Table B-1. (continued).

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
	<b>Sheet-piling barrier</b>	Steel sheet pile technology has evolved to address containment of contamination. Sheet piles are driven, vibrated, or jetted to depth and are constructed with sealable joints to reduce leakage through the sheet pile interlocks. The effectiveness of the sealable joints, including the compatibility with waste, would need to be specifically evaluated. Sheet piles have been used for years in geotechnical applications. Sheet pile panels vary in thickness on the order of 1 cm. Depths up to 23 m (75 ft) are typically attainable, depending on the soil type and density. Depths of 91.4 m (300 ft) are possible in unconsolidated deposits lacking boulders.	The sheet-piling barrier option is effective at minimizing migration of groundwater across the barrier. Permeabilities of $10^{-7}$ cm/s are achievable and $10^{-8}$ to $10^{-9}$ cm/s may be achieved, depending on the soil type. This option can be combined with slurry wall techniques for greater effectiveness.	Sheet piling is a common technology using standard equipment and commercially available materials. Piling could be installed in the near surface soils within the SDA; however, penetration in the underlying basalt to achieve required design depth is questionable. Piling is not implementable around hot spots within a pit or trench because of difficulty driving piles through drums or other containers.	Capital costs are expected to be high in relation to other lateral barriers. Long-term degradation of the piling could require complete periodic replacement.	Not retained—implementability and cost considerations.
	<b>In situ vitrification barrier</b>	In situ vitrification uses electric heat to melt soil into a mass of fused glass similar to obsidian. For barrier wall construction, two or four electrodes inserted into the ground transmit currents to the soil until it melts. The electrodes then sink through the molten soil, advancing the melt zone downward. Panels of soil up to 13.7 m (45 ft) in diameter could be processed at a time. Each succeeding panel would overlap (i.e., melt into) the adjacent panel to increase the areal extent of the barrier. In situ vitrification is a demonstrated technology for processing contaminated soil and buried wastes.	An ISV barrier may be effective at minimizing lateral infiltration if used in combination with surface soil barriers to promote evapotranspiration. The barrier is impermeable to penetration by animals and plant roots. The final cooled product is very durable and impermeable except where fractured. In situ vitrification has not been used as a lateral barrier previously, though the technology has been investigated for such use. <sup>a</sup>	This option is potentially implementable. The availability of ISV equipment is limited and may require project-specific fabrication.	Capital costs are expected to be high in relation to other lateral barriers. The O&M costs are expected to be low in relation to other lateral barriers due to the high durability of the melted zone.	Not retained—process is not demonstrated for this application.
	<b>Ground-freezing barrier</b>	A ground-freezing barrier is implemented by drilling rows of pipes to depth around the containment area. Cooled brine freezes the area between the pipes. A refrigeration plant cools the brine and keeps the system frozen. The refrigeration must be maintained for as long as the barrier is needed. Ground freezing has been used successfully for a number of applications, including drilled shaft construction in high water table areas (temporary applications). The barrier thickness is usually on the order of 9 to 12 m (30 to 40 ft). Depths up to 23 m (75 ft) are attainable, but would be limited by well-drilling capabilities.	This option is potentially effective. If properly designed and operated, the process option would provide a strong, low-permeability barrier around the SDA. Advantages include the ability to turn off the option in the future should new requirements or technologies become available. This option is currently implemented at ORNL for containment of Sr-90 in the HRE pond (DOE 1997).	This option is implementable. Required equipment is commercially available from experienced contractors. Process requires long-term commitment to the O&M Program.	Capital costs are expected to be high in relation to other lateral barriers. The O&M costs are expected to be high in relation to other lateral barriers due to the long design life required.	Not retained—high relative capital and O&M costs.

a. J. Hansen, AMEC's GeoMelt Project Manager for the INEEL, telephone communication with Tami Thomas, CH2MHILL, January 12, 2001

Table B-1. (continued)

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
<b>Subsurface horizontal barrier (in situ liner)</b>	<b>Block displacement</b>	Block displacement vertically displaces a large mass of earth with a low-permeability material. The technique forms a horizontal barrier below the surface by pumping slurry (usually a soil bentonite and water mixture) into a gridded series of notched injection holes. To create a horizontal barrier, high-pressure air is pumped through a notching nozzle extended to the bottom of a borehole drilled to the planned depth of barrier. The air displaces mud and groundwater. Then, sand is injected through the nozzle to erode a notch radially out from the base of the borehole. When the desired notch size has been created, slurry is pumped through the line until the entire notch and casing are filled. Then, additional slurry is pumped under low pressure to lift the ground. The subsurface barrier thickness is generally on the order of 15 cm (6 in.) to over 0.3 m (1 ft).	Block displacement is effective in certain geologic conditions; however, this technology is considered not applicable to the SDA due to the presence of the basalt layer, which immediately underlies the source term in some areas and the unconsolidated nature of the waste. A pilot test would be required to determine whether the zone beneath the waste could be adequately separated for grouting using air pressure or cutting techniques.	The availability of this technology and experienced contractors is limited. The technology may not be implementable due to subsurface conditions within the SDA.	Capital costs are projected to be high. If implementable, multiple applications of the technology would be required to cover disposal areas.	Not retained—process is incompatible with basalt at the base of disposal areas and unconsolidated subsurface (waste) conditions.
	<b>Grout-injection horizontal barrier</b>	The process of using grout as a horizontal subsurface barrier is similar to block displacement, in that grout is pushed through a borehole and injected at depth in a gridded pattern with overlap to achieve horizontal continuity. Viscous liquid barrier is another low-pressure technology, which injects low-viscosity liquid across the interval of the barrier in a similar grid pattern. The viscous liquid flows into pore space in the formation before setting up and sealing off the waste zone. Jet grouting uses a high-pressure pump to inject various grouts radially into the formation across a given interval and again at gridded locations across the zone to be sealed.	This option is potentially effective in basalt materials underlying the SDA. Very low hydraulic conductivities have been demonstrated with grouted barriers. However, it is difficult to verify that the subsurface area has been uniformly treated, and the installation of lysimeters below the grouted zone will be required to verify compliance with RAOs.	This option is potentially implementable. The grout-injection horizontal barrier option requires drilling through the waste or horizontal drilling/coring under the waste. Most grouting techniques could be implemented through drill strings or boreholes, which can be drilled through most areas of the waste. Waste obstruction could limit spacing between boreholes.	Capital costs are expected to be high. If properly designed, the grouted matrix would be stable in the SDA environment and, as such, the O&M costs are projected to be minor.	Retained

Table B-1. (continued)

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
	<b>In situ vitrification liner</b>	In situ vitrification potentially could produce a subsurface horizontal barrier as well as a lateral barrier if the technique involves injecting the starter path at depth and beginning the melt below the waste. For horizontal barrier construction, four electrodes would be inserted vertically in a square or rectangular configuration to a depth below the buried waste. With the application of electrical current to the electrodes, the subsurface starter path would melt and incorporate soil and/or basalt below the starter path into the melt. As the electrodes sink through the molten material, the melt zone would advance downward. Panels up to 13.7 m (45 ft) in diameter could be processed at a time. Each successive melt would overlap (melt into) the previous panels, thereby expanding the ISV barrier until its areal objectives were met.	An in situ vitrification liner probably is not fully effective at minimizing migration of leachates across the barrier. Though the product is very durable and impermeable, the large glass "plate" created will fracture to some extent as a result of shrinkage upon cooling and the effects of seismic activities. The liner has not been used thus far as a subsurface barrier, though the vendor has indicated the viability of such use (Buelt et al. 1987).	In situ vitrification has not been used to produce a subsurface barrier alone, though the subsurface planar configuration illustrates its potential feasibility. A treatability test would be required to determine implementability. Implementation issues are similar to those of ISV for processing buried waste.	Capital costs are expected to be high.	Not retained—not demonstrated for this application.
	<b>Ground-freezing liner</b>	A frozen ground barrier may be constructed to create a subsurface horizontal barrier similar to its use as a lateral barrier. Difficulty may arise from vertical drilling through the waste or horizontal drilling beneath the waste to install brine piping under central areas of the pits. Cooled brine is circulated to freeze the area between the pipes. A refrigeration plant cools the brine and keeps the system frozen. Refrigeration must be maintained for as long as the barrier is needed. The barrier probably would be 1 to 2 m (4 to 6 ft) thick with the attainable area limited by well drilling capabilities. A V-shaped subsurface containment could be created with horizontal drilling into the basalt. <sup>b</sup>	This option is potentially effective. If properly designed and operated, the process option would provide a strong, low-permeability barrier around the SDA. The ground-freezing liner option is currently in use at ORNL. <sup>b</sup> Advantages include the ability to turn off the option in the future should new requirements or technologies become available.	This option is potentially implementable. Required equipment is commercially available from experienced contractors. Brine piping would need to be installed in the basalt under the waste zone. This could be accomplished by drilling through the waste, coring through basalt, and/or horizontal drilling. <sup>b</sup> The process is being implemented at ORNL. <sup>b</sup> Process requires long-term commitment to the O&M Program.	Capital costs are expected to be high. The O&M costs are expected to be high in relation to other lateral barriers due to the long design life required.	Not retained—projected high capital and O&M costs and difficulty with drilling options.

b. D. Magcau, RKK Cryocell, personal communication with Tami Thomas, CH2MHILL, March 6, 2001

Table B-1. (continued).

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
<b>In Situ Treatment</b>						
<b>Physical treatment</b>	<b>Soil vapor extraction</b>	Soil vapor extraction consists of an array of extraction wells, screened within the zone of contamination, that are equipped with an extraction pump capable of pulling enough air to maintain a vacuum within the zone of influence. Soil gases are pulled off and directed into a process train, which treats the gases before emission to the atmosphere. The system can be run intermittently (pulsed) once the extracted mass-removal rate has leveled off. Pulsed operation can increase the effectiveness of the process. Soil vapor extraction addresses only volatile and some semivolatile contaminants and may enhance biodegradation of low-volatility organic compounds. A geosynthetic material may be required over the surface of the SDA during this process to prevent short circuiting (breakthrough at the ground surface). Soil that has a high percentage of fines and a high degree of saturation will require higher vacuums and/or will hinder operation of the process. Application in soils with highly variable permeabilities may exhibit uneven delivery of gas flow resulting in less effectiveness in the lower permeability areas (FRTTR 2001).	Soil vapor extraction is potentially effective at reducing volatile and semivolatile organic contaminants in the source term within the SDA. It preferentially removes materials from high-permeability zones, but can be pulse-operated to allow diffusion to increase removal. Soil vapor extraction is not effective for nonvolatile organics, most inorganics, and radionuclides.  Technology is not suited for buried, containerized wastes. Application in the SDA may require preconditioning of the source term to breach intact containers.	This option is potentially implementable. The SVE system is currently in operation at the site in the underlying vadose zone soils; however, the implementation of this technology directly in the source term is unproven. Treatability testing will be needed to identify off-gas emission treatment requirements.	Capital costs are expected to be low in relation to other in situ treatments. The O&M costs are expected to be moderate in relation to other in situ VOC treatments.	Retained.
	<b>Permeation/low-pressure grouting</b>	Permeation grouting involves injecting low-viscosity grout formulations into the subsurface under gravity feed or low pump pressures. The grout permeates porous media and has been shown to encapsulate waste debris. Previously proven grouts include colloidal silica, polysiloxane, ultra-fine cement-based grouts, and polyacrylamide.	This option is effective. Very low permeabilities can be achieved in porous homogeneous media. At heterogeneous sites, it is difficult to ensure consistent applications across the subsurface.	This option is not implementable for most areas of the SDA. This process depends on the permeability, microstratigraphy, and porosity of the formation to be grouted and is most effective in media with homogeneous characteristics (Hayward Baker 2001).	Capital costs are expected to be low in relation to other in situ treatments. If properly designed, the grouted matrix would be stable in the SDA environment and, as such, O&M costs are projected to be minor.	Not retained due to the extent of low-permeability soil in the SDA.
	<b>High-pressure jet grouting</b>	Jet grouting involves the use of a positive displacement pump to deliver grout to a drill rig, which injects the material into the waste zone through the drill string at 6,000 psi (400 bar). A thrust block—a massive concrete template with holes spaced 61 cm (2 ft) apart on its surface and a void space beneath—is used to ensure that the grid spacing is maintained and workers are protected from returning contaminated grouts. The grout may be injected as the drill casing is inserted and/or as it is removed from full depth. The process requires site characterization and material testing to determine a suitable grouting agent. Many different grouts are available, including chemical grouts, that are injected as solutions rather than suspensions of particles in a fluid medium that defines cementitious grouts (USACE 1995). A dense, low-porosity grout can be used to chemically and physically bind the waste for long-term stabilization.	This option is effective. Jet grouting can be used effectively in soil types ranging from gravel to heavy clays (Mutch, Ash, and Caputi 1997) and has been repeatedly demonstrated on soil and waste sites.  Injection grouting has been demonstrated to significantly reduce hydraulic permeability. In addition, certain grout types chemically alter infiltrating water, thereby reducing the solubility potential of contaminants.  As with other in situ techniques, verification that all areas have been uniformly treated is difficult. This necessitates long-term monitoring of leachate to ensure protectiveness.  Jet grouting can also be used to minimize landfill subsidence, which improves the performance of low-permeability cover systems.	This option is implementable. Process option has been researched for SDA-specific application. Techniques to control the potential spread of contamination resulting from contaminated grout returns have not yet been demonstrated.	Capital costs are expected to be moderate in relation to other in situ treatments. If properly designed, the grouted matrix would be stable in the SDA environment and, as such, the O&M costs are projected to be minor.	Retained.

Table B-1. (continued).

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
	<b>In situ enhanced soil mixing</b>	In situ enhanced soil mixing is a process that has been used to remediate soils contaminated with VOCs, especially those of fine-grained nature. A single-blade auger or a combination of augers ranging from 1 to 4 m (3 to 12 ft) in diameter is used to mix the soils. This process option is combined with a number of other process options to either remove or stabilize COCs in place. The four main options for soil mixing include (1) combination with vapor extraction and ambient air injection, (2) vapor extraction and hot air injection, (3) hydrogen peroxide injection, and (4) grout injection for solidification/stabilization.	In situ enhanced soil mixing is potentially effective at treating COCs, depending on the combination of processes used. With SVE, the mixing can be used to enhance stripping action. In situ peroxidation oxidizes VOCs, while mixing cement grout under pressure can solidify the subsurface mass. However, the effectiveness of this technology in the SDA source term is questionable due to the presence of large metal debris and containerized wastes.	This option has a low implementability. Process option has not been demonstrated in buried waste environment containing TRU waste and HLW. Site-specific designs are required to protect workers and prevent contaminant releases during implementation.	Capital costs are expected to be high in relation to other in situ treatments.	Not retained—process option is considered not implementable on buried wastes within the SDA.
<b>Chemical treatment</b>	<b>Soil flushing</b>	For this process, water is applied to the soil (sometimes with an additive to enhance contaminant solubility). Contaminants are dissolved into the pore water, extracted through wells, and then sent through a treatment train. Co-solvent flushing is an adaptation of soil flushing that uses a solvent mixture (e.g., water plus a miscible organic solvent such as alcohol). The target contaminant groups include inorganics (including radioactive contaminants), though VOCs, SVOCs, fuels, and pesticides also may be treated. The process is more applicable to coarse-grained soil conditions (FRTR 2001).	The effectiveness of soil flushing is low. Water or co-solvent soluble COCs may be dissolved using this method. However, the low permeability of the SDA soil and relative insolubility of many contaminants would inhibit the effectiveness of this process option.	Soil flushing is not implementable. The process requires a flow of water through the waste. In addition, the potential contamination and nuclear criticality hazards could limit its acceptability.	Capital costs are expected to be moderate in relation to other in situ treatments.	Soil flushing has not been retained due to the nature of buried wastes and subsurface conditions within the SDA and risk associated with the mobilization of contaminants resulting from the addition of water to the source term.
	<b>Chemical leaching</b>	Contaminated wastes are leached with appropriate leaching solution and the elutriate is collected in a series of shallow well points or subsurface drains. This process option is more commonly performed as an ex situ technology, thereby eliminating concerns about toxicity of residual leachant.	Chemical leaching is moderately effective. While chemical leaching may result in the mobilization and removal of some COCs, the low permeability of the SDA soil and relative insolubility of contaminants such as Pu-02 would inhibit the effectiveness of this technology.	Chemical leaching is not implementable. As the bottom of the wastes are in contact with or close to the underlying fractured basalt, it would be difficult to collect the elutriate, which, if released, could further contaminate the vadose zone.	Capital costs are expected to be high in relation to other in situ treatments.	Not retained—risk involved with adding water and/or chemicals to the SDA.
	<b>Hydrolysis</b>	Hydrolysis is used to break down certain chemicals by reacting them with water. Many pesticides—including aliphatic halides, amides, carbonates, and others—are susceptible to partial decomposition by hydrolysis (McBride 1994). Use of this mechanism for in situ treatment is primarily related to biological processes, though it has been used for degradation of explosives and has been investigated for immobilization of radioactive elements (Nash 2000).	Hydrolysis is potentially effective. While hydrolysis is a chemical mechanism that could reduce toxicity and/or mobility of certain COCs, with the exception of biologically mediated hydrolysis, this technique has not been proven as an in situ process.	More information is required regarding how the mechanism would be catalyzed and what reaction rates would be achievable for the COCs in the SDA.	Capital costs are expected to be moderate to high in relation to other in situ treatments.	Not retained— process remains experimental in nature.

Table B-1. (continued).

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
	<b>Reduction/oxidation manipulation</b>	Reduction/oxidation reactions chemically convert hazardous contaminants (primarily metals) to less toxic and/or less mobile or inert compounds (CPEO 1998). Materials that can be injected into the subsurface to provide in situ oxidation include iron filings (zero-valent iron) and potassium permanganate grout. In situ reduction/oxidation manipulation creates a treatment zone in the subsurface for remediation of reduction/oxidation-sensitive contaminants in groundwater, including chromate, uranium, technetium, some chlorinated solvents, and some explosive compounds. Aquifer sediments can be chemically manipulated (reduced) so that they become the reactive media. Numerous mechanisms are available for either reducing or oxidizing contaminants. In situ hydrous pyrolysis/oxidation oxidizes DNAPL through the injection of steam and oxygen in contaminated soils (WPI 1998). This process is described below under "Steam Injection."	This option is potentially effective. Reduction/oxidation reactions chemically convert hazardous contaminants to less toxic and/or less mobile or inert compounds. Gaseous reduction is also being tested on chromate-contaminated sites.	This option is moderately implementable. Process is not well tested on contaminants identified at the SDA. The wide variety of contaminants may work against this process, as some contaminants may immobilize on reduction, while others may mobilize.	Process is not cost effective for high contaminant concentrations because of the large amounts of oxidizing agent required (FRTR 2001).	Not retained— process remains experimental and unproven on COCs at the SDA.
<b>Thermal treatment</b>	<b>In situ thermal desorption</b>	In situ thermal desorption combines thermal principles with soil vapor extraction. The subsurface is heated using a number of potential technologies, which include in situ thermal desorption, steam injection, and radio frequency heating. Vapors are extracted via extraction wells, screened within the zone of contamination, and equipped with extraction pumps capable of maintaining a vacuum within the zone of influence. Soil gases are recovered and directed through a process train that treats the gases before emission to the atmosphere, as in traditional SVE (CPEO 1998).	In situ thermal desorption is potentially effective at removing SVOCs and VOCs with an SVE system. The use of ISTD would increase the degree of organic contaminant extraction over that achievable by conventional SVE and potentially destroy other hazardous organic materials by oxidation and pyrolysis. The effectiveness of thermal technologies to support ISTD is discussed below.	This option is potentially implementable. The implementability of specific thermal treatment technologies to support ISTD is discussed below.	Capital costs are expected to be moderate in relation to other in situ treatments.	Retained.
	<b>Thermal conductance</b>	Thermal conductance uses electrical resistance heating elements through rods in a thermal well system. Applications to date have been up to 4.3 m (14 ft) deep (USACE 2000). The waste and contaminated soil are heated to temperatures between 315 and 538°C (600 and 1,000°F) to vaporize and destroy most organics. An aboveground vapor vacuum collection and treatment system destroys or absorbs the remaining organics and vents carbon dioxide and water. Achieving temperatures up to 427°C (800°F) may take 3 months or longer. While generally applied to organic contaminants, the process reportedly "has the potential to chemically stabilize plutonium and other radionuclides and metals and reduce their mobility" (Jorgensen et al. 1999).	Thermal conductance can remove volatile and semivolatile COCs effectively as well as potentially destroy combustible organics, depending on the temperatures and heating times maintained. Vapors are removed and those that are not destroyed are treated in an off-gas treatment train (Jorgensen et al. 1999). However, the effectiveness in treating containerized contaminants remains undetermined.	This option is potentially implementable. Treatability study is required before implementation. Impact on criticality potential requires evaluation.	Capital costs are expected to be high in relation to other in situ treatments.	Retained.
	<b>Steam injection/dynamic underground stripping</b>	Steam injection/DUS targets organics, especially SVOCs and fuels, but also can be used to recover some inorganics. Steam is injected into the subsurface through injection wells. Vaporized contaminants, air, and water are recovered with vacuum extraction wells and treated. The process has been used for years in the petroleum industry to enhance oil field production; its basic aspects are understood. It has been used for remediation at depths between 1.5 and 36.5 m (5 and 120 ft). Dynamic underground stripping has also been used with bioremediation by injecting oxygen after the steam process to enhance microbial metabolism (CPEO 1998; DOE-ID/EM 1997).	Steam injection/DUS effectively vaporizes VOCs and SVOCs in environmental media so that the COCs can be recovered in an off-gas treatment train. The process requires injected steam to contact the surfaces of contaminated soil particles and is therefore dependent on air conductivity of the subsurface. The process has limited applicability in fine-grained materials or in waste zones with irregular permeabilities.	This option is potentially implementable. The process would need to be tested to demonstrate that the COCs would be adequately captured in the recovery and extraction system. In addition, evaluations would have to demonstrate that the steam would not act as a moderator that would increase the potential of a criticality event.	Capital costs are expected to be moderate in relation to other in situ treatments.	Not retained—process option not conducive to waste configuration and fine-grained native soils. Process option could result in mobilization of contaminants from the source term.

Table B-1. (continued).

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
	<b>Radio frequency heating</b>	Like a traditional thermal desorption process, RFH heats soil to volatilize certain organic contaminants, especially VOCs and SVOCs. This process uses radio frequency energy applied through exciter electrodes to heat the subsurface. Closely spaced electrodes are required, as each heating zone has an approximate 1-m (3-ft) radius of influence. Operating temperatures, selected for the target contaminants, are generally on the order of 150°C (302°F), but can reach up to 1,330°C (2,426°F) at exciter electrodes (EPA 1995). Soil gases are recovered with vacuum extraction and directed through a process train, which treats the gases before emission to the atmosphere (as in traditional SVE). Use of the RFH process is limited to the vadose zone and is not effective near or below the water table.	Effectiveness is equivalent to thermal desorption for VOCs, SVOCs, and combustible organics (>250°C) given closely spaced electrodes.	Radio frequency heating is potentially implementable. Treatability study is required to determine effectiveness for containerized waste (Jorgensen et al. 1999). Impact on criticality potential requires evaluation.	Capital costs are expected to be moderate in relation to other in situ treatments.	Retained.
	<b>In situ vitrification</b>	In situ vitrification uses electrical heat to melt soil and waste into a mass of fused glass similar to obsidian. Electrodes inserted into the ground in a square array transmit currents to the soil until it melts, thus volatilizing VOCs and SVOCs and immobilizing other COCs in the process. As the electrodes sink through the molten material, the melt zone advances downward. Off-gases from the process are collected and treated. Planar ISV provides preferential pathways for the escape of vapors between the two planar melts until they fuse together. A 3-m (10-ft) thick cover of unconsolidated materials is maintained over the melt zone in the application of planar ISV. This protects equipment and personnel at the surface from exposure to heat and molten soil expulsions.  Melts up to 13.7 m (45 ft) in diameter have been produced. Melts can be overlapped to treat a large site. The attainable depth of ISV has been increasing as the technology improves. Currently, the deepest ISV melt has penetrated to 8 m (26 ft) below the ground surface (MSE Technology Applications 1999).	In situ vitrification is a demonstrated technology for treating contaminated soil and buried waste. In situ vitrification effectively volatilizes VOCs and SVOCs, pyrolyzes all other organics, and immobilizes most inorganics and radionuclides into inert glass monoliths. Some waste species remain as metals in the melts. The preferred ISV option, planar ISV, shows promise for melting to the required depths and for minimizing molten soil expulsions.	In situ vitrification is potentially implementable. Treatability testing is needed to demonstrate implementability for the SDA. The issues of underground fires and control of molten soil expulsions require resolution. Criticality potential is not thought to be adversely impacted by ISV (Farnsworth 2001).	Capital costs are expected to be moderate to high in relation to other in situ treatments.	Retained.
<b>Electrokinetic treatment</b>	<b>Electrokinetic remediation</b>	Electrokinetic remediation removes metal and radionuclide contaminants from the soil by applying a low-level direct current to the contaminated zone with electrodes placed in the ground. Electrokinetic remediation uses electromigration of ionic species and electro-osmosis. The process works in low-permeability soils, imposing a high degree of control of flow direction as ions move along electric field lines determined by electrode placement. Contaminants are extracted from the circulating electrolytes inside the electrodes.	Effectiveness depends on interfering chemicals and adequate current density (USACE 2000). Electrokinetic remediation may be effective in fine-grained soils where most extraction methods are less efficient (EPA 1999).	This option is difficult to implement. Electrokinetic treatment is a relatively new process that has not been tested for buried waste. Field-scale test results for the U.S. Army were disappointing (USACE 2000).	Capital costs are expected to be high in relation to other in situ treatments.	Not retained—experimental and unproven for buried waste.
<b>Biologic treatment</b>	<b>In situ anaerobic bioremediation</b>	In situ anaerobic biological degradation is generally used for particular contaminants that are not readily degraded by aerobic treatment, such as highly substituted aliphatics and highly chlorinated aromatics including tetrachloroethene, PCBs, and hexachlorobenzene. A typical anaerobic system injects an electron donor substrate into the subsurface (EPA 1999). Airflow into the treatment zone may need to be controlled so that anoxic conditions are maintained.	In situ anaerobic bioremediation can be effective at reducing highly substituted aliphatics and highly chlorinated aromatics and nitrates in groundwater and soils, depending on subsurface conditions. It may not be effective in low-permeability conditions or in containerized waste. This option is not well suited to fine-grained soils (CPEO 1998).	This option may not be implementable because of the difficulty in maintaining anoxic conditions at large scale and the need to inject electron donor substrate (such as acetate) into the subsurface, which may affect criticality potential.	Capital costs are expected to be low in relation to other in situ treatments.	Not retained—process is not well proven for site conditions.

Table B-1. (continued).

Remedial Technology	Process Option	Description	Effectiveness	Implementability	Relative Cost	Screening Comments
	<b>In situ aerobic bioremediation</b>	In situ aerobic biological treatment results in the transformation and/or mineralization of organic contaminants caused by the activities of naturally occurring or specifically engineered microorganisms. Depending on the microbial population and dominant processes, these activities can either break down organic contaminants or mobilize inorganic contaminants for removal. Microbes are affected by temperature, moisture, nutrients, and oxygen, which can be optimized to maximize treatment. Also, specific microbial organisms can be injected to target a particular contaminant. A typical system injects oxygen and/or other nutrients to enhance the growth of microbial populations. Aerobic degradation involves higher metabolic rates and is generally preferred over anaerobic systems. However, the process options may be combined to address particular contaminants that would benefit first from anaerobic degradation, then aerobic degradation (EPA 1999).	This option can be effective at reducing certain aerobically degradable organics, as well as potentially mobilizing metals for recovery. Some chemicals may be degraded to more toxic products: trichloroethene to vinyl chloride (CPEO 1998). In situ aerobic bioremediation may not be effective in low-permeability conditions or in containerized waste.	This option is moderately implementable, but is difficult to control, especially in fine-grained soils (CPEO 1998). Treatability study would be required.	<b>Capital costs are expected to be low in relation to other in situ treatments.</b>	Not retained—process is not well proven for site conditions.
<b>Retrieval</b>						
<b>Contamination control</b>	<b>Confinement/enclosure</b>	Confinement enclosures prevent the spread of airborne contaminants by surrounding or enclosing a piece of equipment, decontamination pad, or an entire site. The enclosures are made of plastic, metal, fiberglass, or other material. These enclosures may be relatively lightweight and portable (e.g., Moducon) or may be substantially more sturdy and less portable (e.g., Butler Building). Enclosures would have to be compatible with the technologies used during remediation.	The confinement/enclosure option is effective in preventing the spread of airborne contaminants during retrieval operations if designed, constructed, and operated correctly.	This option is implementable and readily available. Site-specific enclosure may be required.	Costs will depend on specific conditions and design requirements.	Retained.
	<b>Ventilation/vacuum systems</b>	Ventilation systems use laminar airflow at the digface of an excavation and within enclosures to direct dust to HEPA filter units. Systems would be designed for site-specific conditions and may be used in conjunction with other technologies to minimize the spread of airborne contaminants. Vacuum systems remove loose particles from equipment/structures and draw in dust and debris generated during excavation. Vacuum systems, used to control dust in close proximity to the vacuum, are readily available.	This is a proven process option. It is effective in controlling and directing airborne contaminants and dust away from work areas if designed, constructed, and operated correctly.	This option is implementable. Site-specific design is required. A wide variety of equipment is readily available. Off-gas treatability testing is required to ensure compliance with RAOs.	Costs are expected to be relatively low.	Retained.